1. Introduction

In a recent report to the International Commission on Radiological Protection (ICRP Committee I, 1966), data have been published that provide a better basis for the evaluation of the risks from exposure to radiation than has previously been available. These data are adopted in the following review, which re-evaluates the possible hazard to the population of the United Kingdom from environmental contamination—from nuclear weapon testing or other sources—in terms of the possible incidence of certain types of harmful effect, for example leukaemia. Such an evaluation is inevitably still tentative and is indicative only of the possible upper limits of risk. This review contains an estimate of the total doses that will arise from the fallout in this country from all weapons that have been tested up to the end of 1965, and estimates are given of the risks that may be associated with these doses. The applicability of remedial measures against fallout is also discussed.

The recommendations published by the Medical Research Council in 1960 for the protection of the population against environmental contamination by radioactive substances, especially strontium-90, are reviewed in the light of these estimates, as are the recommendations made in 1962 in relation to problems created by the short-lived radioactive isotope iodine-131. Some additional data on the irradiation of bone marrow due to the incorporation of strontium-90 into bone are included in appendix II.

2. Estimates of risks from radiation

It has been known for many years that a variety of harmful effects may be caused by exposure to radiation. These effects may appear in the individual exposed (somatic effects), or they may be passed on to subsequent generations as a result of alterations in the genetic material (genetic effects). The recent report to the International Commission deals with the genetic and delayed somatic effects that might be expected from exposure to moderate or low doses.

(a) *Somatic effects*

The most important of these effects on the individual is to cause an increased risk of the induction of cancer and in particular leukaemia (which may be regarded as a cancer of the blood-forming tissues). Quantitative evidence has been accumulating over the past decade about the incidence of cancer in man at radiation doses and dose rates hundreds of times higher than those now under consideration, notably from long-term follow-up studies of the exposed populations of Hiroshima and Nagasaki and from studies of patients who have received radiation treatment for ankylosing spondylitis. By assuming that the response per unit dose of radiation is similar at low doses to that at much higher doses—that is to say, that the ratio of effects to dose remains constant—the possible risks from exposure to low doses such as might result from present levels of fallout may be estimated. It is to be noted that such a procedure may grossly overestimate the effects of low doses of radiation, since there are grounds for believing that the response per unit dose is likely to be lower at low doses than at high doses and furthermore that the effect of radiation decreases with decreasing dose rate in this low range.

The estimates of risk made in the report to the International Commission have been expressed in terms of the numbers of additional cases of leukaemia, of thyroid cancer and of all fatal cancers taken together that might be expected over and above the natural incidence if a population of one million persons were exposed to one rad of radiation to the whole body or a substantial part of it. This is about ten times the dose that is received on average by every individual in this country from natural background radiation each year. The available information suggests that, following such exposure, a total of twenty additional cases of leukaemia might occur, spread over the following 10–20 years. The additional incidence of all other fatal malignancies is judged to be similar to that of leukaemia, and so might add a further 20 cases per million persons exposed.

Information on the incidence of cancer of the thyroid has been obtained primarily from effects on children following therapeutic medical exposure in infancy. On this basis, the report concludes that there is a risk of 10–20 additional cases in a population of one million persons exposed to one rad. The risk of occurrence of thyroid cancer thus appears to be comparable to that of deaths from leukaemia, or from all types of fatal cancer other than leukaemia taken together. However, it is to be noted that, in contrast to the other conditions mentioned, thyroid cancer of the type induced by irradiation in infancy can commonly be treated successfully and the mortality from it would therefore be very considerably less.

The above figures refer to the increased incidence over and above the natural incidence in the United Kingdom of all types of fatal cancer (including leukaemia), the figure for which is at present about 2200 cases per million persons per year.

(*b*) *Genetic effects*

The frequency of genetic effects of radiation, particularly from small doses, is even more difficult to assess than that of the somatic effects considered above. There are no human data yet available that are comparable to those on the somatic effects. Extensive surveys have been made of the populations of Hiroshima and Nagasaki and of other human populations exposed to higher than normal radiation doses, but none of these has revealed any unequivocal evidence of harmful genetic effects of radiation. Thus any assessment at the present time is still dependent mainly on inference from animal experiments. As this approach may introduce substantial uncertainties, it is not yet possible to assess the relative importance of genetic and somatic effects in man.

The evaluation of the genetic effects of radiation is further complicated by the fact that they may take a wide variety of forms. The common factor assumed to be responsible is the induction of mutation in single genes or chromosomes, involving a qualitative or quantitative change in part of the genetic material that is capable of being transmitted to at least one generation.

The harmful effects cannot be correlated with any single physical characteristic because they are so varied and complex, and may be distributed over a single generation or over many. In addition to the production of a wide range of well recognised congenital defects they may, for example, contribute to undetectable failures of early fertilised ova to implant, as well as to abortions, stillbirths or early postnatal deaths. In addition, mutations may have an unfavourable effect on physical and intellectual development. Such impairment of what might have been the potential of an individual would have no distinctive characteristics and would be very difficult to detect. It is not considered practicable in the present state of knowledge to make estimates of the total numbers of cases in all these categories that might result from radiation doses. However, the report to the International Commission makes tentative estimates of the numbers of the more serious physical defects which might be expected to occur in the first generation of offspring of irradiated parents. The exposure of parents to one rad of whole body radiation is estimated as being likely to produce in the first generation an increased incidence of about twenty cases of " visible " genetic defects per million live births. These defects would be expected to appear during a score or more years.

A comparable figure for the natural incidence of visible genetic abnormality is about 15 000 per million live births. The irradiation of a population group to the extent of 1 rad may therefore be estimated to increase the risk of such defects occurring in the first generation by about one case amongst 750 arising from natural causes. The total genetic damage occurring over many generations will, however, be considerably more than the above estimate of the incidence of visible defects in the first generation. The total damage per generation would be greatest in the first generation, but both visible and other defects would continue to occur in subsequent generations, although at a progressively lower rate.

3. Risk associated with fallout from weapon tests

Appendix I gives estimates for members of the population of the United Kingdom of the " dose commitments "—that is, of the total doses that they will ultimately have received from the fallout resulting from all weapon tests that have been carried out up to the end of 1965. These estimates of dose commitment refer to the country-wide average for persons living throughout the entire period 1954–2000. Differences will occur between individuals because the deposition of fallout varies with rainfall, and agricultural factors influence the transfer of radioactive materials into foodstuffs ; dietary habits may cause further variations in internal exposure, and the types of building in which people reside can influence the external dose. However, these variables can have a larger effect on the doses received during relatively short periods than on the life-time dose commitment.

The dose commitments up to the year 2000 are seen to be comparable with the doses to the various body tissues received in one year from natural background radiation (see table 1, appendix I).

By combining this assessment of dose commitment with the estimate of the upper limit of risk per unit dose, the maximum number of cases of various diseases that may occur per million of the population can be derived. Strictly this maximum risk could apply only to members of the population living through the entire period from the commencement of nuclear weapon testing until the year 2000, since the dose commitment values given in appendix I relate to exposure throughout the whole of this period.

It should be noted that the ratio of the dose commitment for endosteal tissues to that for bone marrow is about 1·2. It follows therefore from the evidence presented in appendix II on the relative susceptibilities of these tissues that the risk of induction of leukaemia is likely to be greater than that of bone cancer. Even if strontium-90 is considered alone therefore it now appears that leukaemia rather than bone cancer should be regarded as the limiting risk (see appendix II).

(*a*) *Risk of leukaemia*

Exposure to all components of fallout reached a maximum in 1963. The results of dietary surveys indicate that, although intake of long-lived nuclides was similar in 1964 to 1963, it declined appreciably in 1965. The total dose commitment to bone marrow to be expected as a result of all tests conducted up to the end of 1965 is likely to be somewhat less than 0·15 rad. On the basis of the risk estimates described, the additional cases of leukaemia should thus not exceed 3 cases per million exposed, and they may be very much less.

(*b*) *Risk of other fatal malignancies*

The dose commitment for the body as a whole to be expected from all constituents of fallout is estimated as about 0·1 rad. In the light of present knowledge the likely upper limit to the number of additional cases of fatal malignancies other than leukaemia appears to be of the order of 2 cases per million ; it may be somewhat more because of the long induction period for these conditions, and the incidence may be very much less if there is a falling off of response at low dose rates.

(*c*) *Risk of the development of thyroid cancer*

Owing to the short radioactive half-life of iodine-131 (8 days), radiation doses from this source are delivered only during a relatively short period after weapon trials. The results of dietary surveys indicate that, both in 1961 and in 1962, the average dose to the thyroid glands of young children who depended on fresh milk was about 0·1 rad from this source, although the average dose throughout the population will have been much lower—about 0·01 rad. For the period to the year 2000, the dose commitment for the thyroid from all other sources is estimated to be about 0·1 rad. From the current assessment the risk of subsequent thyroid cancer would not exceed two cases per million people, any mortality from this condition being considerably less (and already included in (*b*) above).

(*d*) *Genetic risk*

The dose to the gonads of members of the present generation from the fallout from all tests up to 1965 will not exceed about 0·1 rad. (Many subsequent generations will be subjected to very low annual doses from carbon-14, the total additional dose over these generations being about 0·2 rad.) In the case of the present generation, it may be estimated that about one additional case of visible genetic abnormality could be caused in the offspring of each million persons exposed, since 0·1 rad might cause 2 such cases in one million live births, and this number of live births might be expected to occur in a population of about 2 million people of all ages.

4. Earlier standards of assessment

The standards commonly used up to the present time for the assessment of fallout levels have been the 1960 recommendations of the Medical Research Council for the protection of the population against environmental contamination with radioactive substances, especially strontium-90. In 1962 the Council considered the problems created by the short-lived radioactive isotope iodine-131. The Council's advice regarding maximum permissible levels of radiation from these components of fallout for members of the population was based largely on the principles that had been developed by the International Commission on Radiological Protection. The maximum permissible levels for occupationally exposed persons were then defined by the International Commission as those " which in the light of present knowledge carry a negligible probability of severe somatic or genetic injury ". Although the levels then specified by the Commission were intended to prescribe limits to occupational exposure to radiation and to planned releases of radioactive effluent such as might occur during the normal operations of nuclear installations, laboratories and industrial establishments, the Council considered that they could also serve as a criterion for reviewing the risks from environmental contamination due to fallout from nuclear weapon testing. The levels recommended by the Medical Research Council for individual members of the population and for the population as a whole were lower than the occupational level by factors of 10 and 30 respectively. It follows therefore that these two sets of levels were associated with very low orders of risk and, as is apparent from earlier sections, this assumption has been borne out by the recent risk estimates.

5. Current recommendations of the International Commission

The Commission have recently revised their recommendations for the protection of persons exposed to radiation and have drawn a clear distinction between sources of exposure that are controllable and those that are not subject to control (ICRP, 1966). Under normal conditions, direct control of the exposure of workers to radiation is practicable in the industrial or clinical use of nuclear energy by the development of proper operational procedures. For such situations, the Commission refer to " maximum permissible doses " for persons who are occupationally exposed to radiation and to the dose limits appropriate for members of the public in relation to exposure from planned discharges into the environment. In contrast, however, the principle of adhering to a fixed maximum permissible dose is not applicable in situations when an environmental contamination has already occurred—for example as a result of an accident at a nuclear establishment or following the testing of nuclear weapons. The radiation doses received by the population from such sources can then be limited only, if at all, by remedial action, which might involve changes in the habits of life or source of diet of the people affected. The Commission propose that the basic principle that should guide action in these circumstances is that the hazard and social cost involved in any such remedial measure must be justified by the reduction of risks that would result. Because of the variability of the circumstances in which remedial action might be considered, the International Commission have decided that it would be impossible to recommend fixed radiation levels at which it would be appropriate to take action on all occasions. Certain remedial measures, however, which have thus far appeared to merit investigation as practical possibilities for the protection of members of the general population are considered below in relation to the views of the International Commission.

6. Countermeasures against fallout

In considering countermeasures that might be adopted if remedial action were judged necessary on account of environmental contamination, it is convenient to consider the position in regard to iodine-131 separately from that of strontium-90 and other components of fallout.

(*a*) *Iodine*-131

The thyroid glands of infants receive considerably higher radiation doses from iodine-131 than do those of older members of the population. Since fresh cow's milk is the dominant route of iodine-131 to the body, the substitution of dried for fresh cow's milk in the diet of infants would provide a large measure of protection. The storage of dried milk for a short time would confer a high degree of protection because the activity of the iodine-131 decreases by a factor of about 15 in every month. It is not anticipated that any significant health hazard would be involved if dried milk were supplied to infants instead of fresh cow's milk. It is important to note, however, that these measures would have little effect on the doses to the thyroid from nuclides other than iodine-131. Experience from the weapon tests of 1961 and 1962 has shown that these nuclides contribute about one-third of the total dose to the thyroid in infants and most of the total thyroid dose in adults.

In countries such as the United Kingdom where the organisation exists for the provision of special foods for infants, the institution of this type of remedial action would be practicable at relatively short notice. Action of this type was planned in 1961 when it was considered necessary to envisage the possibility that contamination with this radioactive isotope would exceed the limit specified by the Medical Research Council. In the event, however, no action was required.

(*b*) *Other radioactive isotopes*

Remedial action against other radioactive isotopes raises entirely different kinds of problems. Strontium-90 has the comparatively long radioactive half-life of 28 years and it may persist in the environment and continue to contaminate articles of diet, particularly milk, for long periods. Any measures designed to prevent its incorporation into the human body would therefore have to be continued for long periods, possibly years, in contrast to the periods of a few weeks only for any release of radioiodine.

The highest concentrations of strontium-90 have so far been found in the bones of young children aged between 1 and 2 years. Children of about this age may therefore be regarded as the section of the population at the greatest risk initially and the one which should be considered first if there should be any question of instituting remedial measures.

It is known from previous investigations that cow's milk has been the main source of strontium-90 in the diet of young children. Attention has accordingly been focussed on the possibility of reducing levels of contamination of milk supplies.

In areas where comparatively high levels of contamination of milk had occurred, the substitution of milk from relatively uncontaminated areas would give some protection, provided that unacceptable levels were experienced only on a local scale. Such a procedure would, however, clearly cease to be effective if high levels were reached on a wide scale—that is, nationally or in a major milk-producing zone.

Consideration has therefore been given both in the United States and in this country to the removal of strontium-90 and caesium-137 from milk by treatment by an ion-exchange process. However, a fundamental difficulty is that such a process could at best only provide a high degree of protection against the radiation dose from ingested strontium-90 or caesium-137 in the very earliest months of life, when cow's milk was the main article of diet. As soon as mixed feeding was introduced, about half the intake of both strontium-90 and caesium-137 would in any case come from other sources than milk. Moreover, strontium-90 and caesium-137 cannot be usefully considered in isolation, since the ingestion of these from fallout is responsible for only about one-half of the radiation dose to bone marrow (see appendix I). Thus even their complete elimination from all foodstuffs—were this possible—would give only partial protection.

Some consideration has also been given to the practicability of modifying agricultural procedures to reduce the level of contamination of crops or animal produce. It has, however, been concluded that no method that would be practicable on a large scale is likely to provide more than a small degree of protection against contamination by either strontium-90 or caesium-137.

Other remedial measures that are currently under examination are those designed to inhibit selectively the uptake into the body of strontium-90 from diet. Thus the supplementation of the diet by calcium in various chemical forms has been considered ; but it is clear from the experiments so far carried out that this method would again be unlikely to afford a greater degree of protection than about a 50 per cent reduction in the total strontium-90 uptake from all articles of diet. The advantage of such methods of dietary supplementation might be that they could be applied on a very large scale at comparatively little cost. However, the possibility that they might not be altogether without harm to certain—probably small—sections of the population must be borne in mind, and it seems impossible at the present stage of knowledge to calculate even approximately the scale of any ill effects on health.

While therefore the effectiveness of these and other possible countermeasures against fallout are continuing to receive attention, it appears unlikely in the present state of knowledge that any large-scale and prolonged remedial action against the somatic effects of strontium-90 and other components of fallout could be readily devised. Protection against the genetic effects would be still more difficult, since these are attributable primarily to external radiation and ingested caesium-137. It should be noted that, except in the early months of life, a large fraction of the caesium-137 that enters the body is contained in components of diet other than milk, and any attempt at decontaminating these components would involve major dislocation of normal food supplies.

7. Discussion

The information that is now becoming available on the possible risks from low doses of radiation enables the implications of the exposure of the population to fallout to be assessed on a more direct and generally understandable basis than that of the standards recommended in 1960 by the Medical Research Council. Following the current terminology of the International Commission, these standards were then described as " maximum permissible levels ", a term which in the intervening years has sometimes (and incorrectly) been regarded as synonymous with " danger levels ". The currently accepted concept of a linear relationship between radiation dose and frequency of resulting effect—as opposed to that of a " threshold " below which biological effects would not occur—implies that there would not be a sudden transition from a situation of

" safety " to one of " danger " at any particular fixed level, and indeed that even the lowest radiation doses cannot be regarded as being absolutely " safe " in the sense of being entirely free from risk. This applies equally to exposure to natural and to man-made sources of radiation ; a comparison of these exposures is made in appendix I of this report.

The precise point at which it would be appropriate to take remedial action to limit the exposure of the population to radiation from environmental contamination would depend primarily on the general trend of contamination levels in a particular situation and on the current position regarding the development of remedial measures. In the event of any further large-scale nuclear tests in the atmosphere, the fallout levels following a particular series would depend on the type, scale, location and timing of the tests that were made as well as on the local and seasonal meteorological conditions obtaining in this country for some time afterwards. It is therefore impossible to estimate with any confidence the levels that might be reached. Further, the possible remedial measures discussed above in section 6 could at best be only partially effective, and their adoption could never guarantee that the exposure of any section of the population to radiation could be kept below a fixed level. The higher the levels of fallout over a widespread area the more difficult it would be, with the methods at present available, to control the resulting radiation doses. There is, moreover, the possibility that risks at least comparable to those resulting from the radiation exposure might be associated with the countermeasures themselves.

As explained in section 5, the International Commission on Radiological Protection has concluded that it is not feasible to recommend fixed levels at which action should be taken that would be appropriate for all occasions. The Medical Research Council have accepted this conclusion* and consider that any decision about the institution of remedial measures can be taken only when as many as possible of the factors relating to a particular case are known. It would then be necessary to balance, so far as is practicable, the anticipated risk from radiation against the risks and social disadvantages that might result from the implementation of particular countermeasures.

May 1966

Signed on behalf of the Committee,
JOHN COCKCROFT
Chairman

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* This conclusion is substantially similar to that reached by the Federal Radiation Council of the United States of America, which makes no recommendation about particular levels at which remedial action should be taken against strontium-90 from world-wide fallout.

APPENDIX I

Radiation doses in the United Kingdom from fallout due to all past weapon testing

To estimate for the population of the United Kingdom the " dose commitment* "—that is, the total radiation dose to which human tissues have been committed as a result of nuclear testing—it is necessary to take account not only of those radiation doses that have already been received but also of those that will be sustained in the future. These latter arise from three sources : nuclides already present in the body; nuclides now present in the earth's surface, which will deliver radiation doses in the future ; and nuclides that have yet to be deposited from the stratosphere. The main problems are in predicting the magnitude of the doses that will arise many years hence ; estimates are of necessity based on indirect evidence and extrapolations are subject to much uncertainty.

An approximate indication of the future fallout from tests already carried out can be obtained from the stratospheric surveys of strontium-90 carried out by the United States and reviewed by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR, 1964, tables III and IV) and also from more recent data (USAEC, 1965 ; Feely and Bazan, 1965 ; Cambray *et al.*, 1965). From these data it appears that the strontium-90 content of the stratosphere at the end of 1965 is unlikely to have amounted to more than some 25 per cent of that already deposited and a proportionate allowance has accordingly been made on this basis in the present calculation of dose commitment for strontium-90 and caesium-137.

Table 1 sets out calculations of the dose commitments for the population of the United Kingdom that will result from the principal sources of internal and external radiation except iodine-131, which is considered separately. For purposes of comparison the periods in which the same doses will be received from exposure to natural background radiation in this country are given in the table.

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* The term " dose commitment " is discussed in the UNSCEAR report (1962, p. 416), but is not defined in detail analytically. An approximate calculation is made here on the basis of the following formula :

$$D = (D_e + D_i)_{1954} + \dots . (D_e + D_i)_{1965} + R(1966–2000),$$

where D_e and D_i are the actual doses received, from external and internal fallout respectively, in the years indicated and R is the residual dose for the years 1966–2000. The dose commitment D refers to a given tissue regarded as existing over the whole period, and an approximate allowance for the effect of age is made by basing D_i on representative average values of ingested activity. There are clearly other factors (such as age at time of intake, population changes with time, variation of dose factors and tissue sensitivity with age, etc.) that would need to be included in a more refined evaluation. In view of the uncertainties in the biological bases of estimating risk, such refinement would at present be unjustified.

TABLE 1

*Anticipated total dose commitments to the population of the United Kingdom from fallout nuclides (other than iodine-*131)

	Bone (mrad)	Endosteal tissues (mrad)	Bone marrow (mrad)	Gonads and other tissues (mrad)
Strontium-90	140	62	40	—
Caesium-137 : internal	23	23	23	23
external	27	27	27	27
Short-lived isotopes : external	17	17	17	17
Carbon-14*	31	20	13	13
Total	238	149	120	80
Approximate periods (years) in which these doses are received from background radiation	2·4	1·5	1·2	0·8

* Estimated dose to the year 2000.

Strontium-89 has been excluded from the assessment since, despite the fact that it may deliver appreciable doses during short periods, it is evident from the assessment of UNSCEAR (1964) that the integrated dose from this nuclide is less than 1 per cent of that from strontium-90 and is thus small in relation to uncertainties in the assessment of the latter. Barium-140 would give a still smaller dose and has been similarly excluded.

In a number of respects this assessment follows the procedures adopted by UNSCEAR (1962, 1964) in calculating the dose commitment for the world population. However, the situation in the United Kingdom differs from the world average because the quantity of fallout deposited varies appreciably with latitude and also because dietary composition and agricultural practices determine the fraction of fission products that are ingested. Both for these reasons and because additional information has recently become available on some aspects, the present estimates of doses that may be received by the population in the United Kingdom differ appreciably from those formerly estimated for the world population by UNSCEAR.

It should be pointed out that the dose commitments given in table 1 for the whole population refer to persons born before nuclear weapon testing began and still alive by the year 2000. In fact about two-thirds of the dose commitment will already have been received by those who live only until 1975.

STRONTIUM-90

The levels of strontium-90 in milk have been chosen as a basis of calculation for the following reasons. The past levels in milk are known with considerably greater certainty than those in other items of diet or in bone because of the much more elaborate sampling that is possible ; and milk is the major dietary source of strontium-90 for the infant population. Moreover, the ratio of strontium-90 to calcium in milk can be regarded as representative of that in mixed diet for the whole population.

TABLE 2

Integrated country-wide levels of strontium-90 in milk in the United Kingdom due to past weapon testing

	pCi-years ⁹⁰Sr/g Ca
From fallout deposited up to the end of 1965 :	
1953–65 (observed)	130
After 1965 (calculated)	170
From fallout deposited after 1965	75
Total	375*

* This may be an overestimate by 20 per cent (see text).

In table 2 the integrated country-wide levels of strontium-90 in milk (pCi-years ^{90}Sr/g Ca) are shown for the period during which observations have been made, namely from 1953 to the end of 1965. The values for the years before 1957 are based on very limited information (Bryant *et al.*, 1957) but values for the period from 1958 onwards are derived from the much extended country-wide survey that was introduced in 1958 (Agricultural Research Council Radiobiological Laboratory, 1965) ; because only a small fraction of the total strontium-90 that has hitherto reached milk originated before 1957, the uncertainty of the data for the early years is only a minor source of error.

Table 2 also shows the expected total of strontium-90 that will reach milk in consequence of the fallout deposited by the end of 1965 ; this figure has been derived from the measured deposit of strontium-90 by the proportionality factors that relate the ratio of strontium-90 to calcium in milk to the recent deposit and the cumulative total of fallout (Bartlett and Russell, 1966). A recent reassessment of these factors shows that the cumulative deposit of strontium-90 in the soil makes a smaller contribution than was formerly supposed, the effect of the direct contamination of plants by the recent deposit being correspondingly greater. It has here been assumed, following UNSCEAR (1962), that the absorption of strontium-90 by plants will, on average, be reduced by about 2 per cent per annum through leaching and other processes. This assumption may cause the dose commitment from strontium-90 in the United Kingdom to be overestimated by perhaps 20 per cent, since climatic and agricultural conditions in this country may lead to an annual reduction greater than 2 per cent (Loutit *et al.*, 1960).

As explained in the second paragraph, future fallout may amount to a total of 25 per cent of that which has occurred so far. Thus it is assumed that future fallout will increase the strontium-90 in milk to the total of 375 pCi-years ^{90}Sr/g Ca given in table 2. To calculate the resulting dose commitments from strontium-90 to bone, endosteal tissues and bone marrow, the method of UNSCEAR (1964, paragraphs 170–173) has been employed, except that it has been assumed that 1 pCi ^{90}Sr/g Ca in bone will give rise to the following dose rates : 2·5 mrad/y in bone, 1·1 mrad/y in endosteal tissues and 0·7 mrad/y in bone marrow. These values are interpolations between the values given in appendix II for adults and for children, since it is demonstrable that there is no considerable variation in dose commitment per microcurie ingested at various ages. The dose commitments from strontium-90, calculated on this basis, are given in table 1.

(*a*) *Internal doses*

The assessment of internal radiation doses received from caesium-137 is considerably easier than for strontium-90 since they may be estimated from measurements of whole-body radioactivity in living subjects and comparable doses are received by all age groups except very young children ; in the early months of life, the dose rate is appreciably lower but this has little effect on the life-time dose commitment. The integrated dose received by a group of adult subjects measured at regular intervals in Berkshire between the years 1957 and 1965 has been estimated at 11·4 mrad (Rundo, 1960 ; Rundo and Newton, 1962, 1964 and unpublished data). A comparable figure may be derived from the measurements made in a different group of subjects in Surrey (Vennart, 1966). Since internal doses from caesium-137 vary between different parts of the United Kingdom, primarily on account of the differences in the contamination of milk due to rainfall, the Berkshire estimate has been adjusted to give figures more representative of a country-wide average. The resultant dose received by the population of the United Kingdom in the years 1957-65 is therefore estimated as 14 mrad.

The integrated country-wide level of caesium-137 in milk between 1957 and 1965—the period when the whole-body measurements were made—is 600 pCi-years ^{137}Cs/l. From the incomplete dietary data available for the years before 1957, it appears that an integrated total of 45 pCi-years ^{137}Cs/l may have entered milk prior to 1957 and it can be estimated (Bartlett and Russell, 1966) that fallout that occurred before the end of 1965 may cause a further 150 pCi-years ^{137}Cs/l in milk in the future. Thus the total contamination of milk due to fallout that has occurred hitherto should be about 800 pCi-years ^{137}Cs/l ; if it is assumed (as with strontium-90) that future fallout will amount to approximately 25 per cent of that which has occurred so far, the integrated total commitment of caesium-137 in milk is estimated at 1000 pCi-years ^{137}Cs/l.

On this basis the total dose commitment from ingested caesium-137 in the United Kingdom is estimated at 23 mrad. As with strontium-90, uncertainties regarding the behaviour of caesium-137 in the soil in distant years may have caused some overestimation of the integrated dose.

(*b*) *External doses*

The method of calculation used by UNSCEAR (1964, paragraph 164) has been adopted but has been adjusted to the conditions of fallout in the United Kingdom. No population-weighting factor is required and it has been assumed that the fallout after December 1965 will be 25 per cent of the fallout deposited before that date. A shielding and screening factor of $\frac{1}{5}$ has been used (Medical Research Council, 1960, p. 88). On this basis the estimated dose commitment for the United Kingdom is 27 mrad.

EXTERNAL RADIATION FROM SHORT-LIVED NUCLIDES

The external radiation doses from short-lived nuclides in fallout have been derived from direct measurements of the radiation dose over grassland in Berkshire (Gibson, 1964, and unpublished data). The monthly dose rates, less the calculated component due to caesium-137 accumulated on the ground, have been summed over the years 1961–65. The resulting dose has been increased in proportion to the average annual rainfall of the United Kingdom compared with that in Berkshire (40 in/28 in). A further increase of 50 per cent has been made to allow for the contribution from tests prior to 1959 (see UNSCEAR, 1964, table III). The same shielding and screening factor (⅛) has been used as for caesium-137. The estimated dose commitment is 17 mrad.

CARBON-14

Doses from carbon-14 have been calculated up to the year 2000 by the method used by UNSCEAR (1964, paragraphs 86-88). There will be a further contribution to the dose commitment from carbon-14 after the year 2000 ; this will be delivered at an exceedingly low rate and has not been included in table 1.

In contrast with the other continuing sources of exposure, the major part of the anticipated dose from carbon-14 will not be delivered until after many centuries. Quantitative assessments are beset with considerable uncertainty as they rest on the assumed rate of equilibration of carbon-14 between the atmosphere and biological pools of carbon in the earth's surface, especially in the deep oceans. UNSCEAR (1964) concluded that only 7 per cent of the total radiation dose from carbon-14 might be delivered by the year 2000, at which time carbon-14 released in past weapon testing would equal about 3 per cent of the natural carbon-14 content of the atmosphere.

In judging the radiological significance of this situation it is relevant to note that naturally occurring carbon-14 accounts for about 1 per cent of the total natural background radiation received by the gonads or bone marrow ; moreover, the increase in the atmospheric content of carbon-14 due to past weapon testing that is anticipated by the year 2000 is comparable to the estimated decrease that has occurred in the past half century because of dilution by the release into the atmosphere of carbon from fossil fuels from which carbon-14 had disappeared by decay (Suess, 1955).

IODINE-131

Iodine-131 is considered separately from table 1, partly because it is of concern with respect to young children, for whom fresh milk may be a major component of diet, and partly because the doses are received during only brief periods, shortly after weapons trials. In 1961 and 1962 the mean integrated intakes of iodine-131 by infants in the first year of life, who depend on fresh milk, was estimated at about 5700 and 4800 pCi respectively, leading to radiation doses of about 0·1 rad in each year. These doses are not directly additive as the exposure of children in the second year of life is considerably smaller. Moreover, the consumption of dried milk will have reduced the mean dose to the infant population by about half.

No comparable estimates of radiation doses received as a result of iodine-131 from weapon testing in earlier years are available. As in the case of doses from other short-lived nuclides, it is possible that doses amounting to approximately 50 per cent of those quoted are likely to have been incurred from tests prior to 1959.

APPENDIX II

The dose rates to relevant tissues in bone from strontium-90 and strontium-89

When bone is irradiated the long-term effects, observed in man and in animals, are the development of bone tumours and leukaemia. The type of effect, however, depends on the nature of the radiation. Radium is known to produce bone tumours in man, but there has been no unequivocal evidence of leukaemia. On the other hand the production of leukaemia rather than bone tumours has been found to be the greater risk when the individual is exposed to irradiation of the whole body or of a large part of it. In the case of the Japanese survivors of the atomic bombing of Hiroshima and Nagasaki, the total incidence of radiation-induced chronic myeloid and acute leukaemia, which presumably arise from irradiation of bone marrow, is approximately as great (at the present time) as all other fatal radiation-induced tumours put together, and the other tumours do not include a large proportion of bone cancer (ICRP, 1966). In the survey of patients treated with X-rays for ankylosing spondylitis, the predominant radiation-induced effect was found to be leukaemia and the number of such cases greatly exceeded the number of bone tumours. There is no direct evidence of the effects of strontium-90 in man, but in animals both bone tumours and leukaemia are observed, the incidence of leukaemia being more noticeable in investigations where strontium-90 is administered to animals regularly, as in food, over long periods of time.

A recent review (Vaughan, 1964) presents considerable evidence that radiation-induced osteogenic tumours in animals arise in endosteal tissues, rather than in periosteal tissues or in cells of Haversian systems, and this directs attention to trabecular bone, where the primitive osteoprogenitor cells lie close to trabecular (i.e. endosteal) surfaces. It is also reasonable to suppose that leukaemia, developing from cells of the active bone marrow, may arise from cells anywhere in the intertrabecular cavities.

It is therefore to be expected that radium incorporated in the bone matrix will give rise to bone tumours, because the α-particles emitted can irradiate endosteal tissues, which lie close to bone surfaces. Radium is, however, much less likely to induce leukaemia because most of the active marrow in cavities 500 μ to 1000 μ across lies beyond the range of the α-particles ($\sim$40 μ) emitted from the trabecular surface.

On the other hand, penetrating external radiation gives equal doses to endosteal tissues and to bone marrow and the follow-up of the Hiroshima and Nagasaki survivors indicates that, for equal doses, there is a very much greater susceptibility to leukaemia than to bone tumours. This conclusion is reinforced by the studies on cases of ankylosing spondylitis, where the induction of leukaemia predominates over that of bone tumours, despite the fact that endosteal cells that lie close to bone surfaces receive a higher X-ray dose than do the cells of the bone marrow. (The dose ratio for endosteal cells/bone marrow is about 1·5 for X-rays generated at 200–250 kVp and falls to 1·0 for X-rays and γ-rays above 0·5 MeV photon energy.)

In the case of strontium-90 + yttrium-90 the mean β-particle range is about 5 mm, which is large compared with the linear dimensions of the marrow cavities in trabecular bone. Both endosteal tissues and bone marrow are therefore irradiated when strontium-90 is incorporated in the bone matrix, and the circumstances are closer to the irradiation of bone by external X-rays than by α-particles from radium. These considerations have led us to conclude that leukaemia and not bone cancer may, in man, be the major risk from strontium-90 and other high energy β-emitting bone-seeking isotopes. It is of interest that the recently published reports of the United States Federal Radiation Council also assume the bone marrow to be the critical tissue for strontium-90 in the skeleton.

The radiation dose rates to relevant tissues in bone have therefore been calculated for a uniform contamination of 1 pCi ^{90}Sr/g Ca. This has been done by a method that takes into account the effect of the distribution of marrow cavity size on the radiation dose rate delivered by β-particles to the endosteal surfaces and to bone marrow (Spiers, 1966). The mensuration of the trabecular and cortical structures of a number of bones has enabled average dose rates to be determined for the skeleton of an adult and of a child aged 5 years. The results are given in the table for both strontium-90 and strontium-89, although the values for strontium-89 are approximations, derived from those for strontium-90 on the basis of relative β-particle energies and ranges.

Whereas the dose rate to bone (strictly to the mineralised bone matrix) for a skeletal content of 1 pCi ^{90}Sr/g Ca is usually taken to be 2·7 mrad/y (UNSCEAR, 1962), the mean dose rate to active bone marrow is 0·55 mrad/y for the adult and 0·82 mrad/y for the child (see table 3). For strontium-90 the ratio of the endosteal dose rate to the mean marrow dose rate is about 2 for the adult and 1·3 for the child ; these ratios are not very different from the ratio 1·5 for the X-rays used to treat ankylosing spondylitis, but are very much less than the ratio of about 10 for radium α-particles. The corresponding ratios are higher for strontium-89, but this isotope makes a much smaller contribution to the dose to tissues in bone than does strontium-90.

TABLE 3

Dose rates to bone tissues from 1 pCi ^{90}Sr and ^{89}Sr/g Ca

Tissues in bone	Dose rates for 1 pCi/g Ca in mrad/y			
	Strontium-90		Strontium-89	
	Adult	Child	Adult	Child
Mineralised matrix	2·7	2·0*	1·35	1·0*
Bone marrow (average for skeleton)	0·55	0·82	0·11	0·17
Endosteal tissues (average for skeleton)	1·13	1·08	0·49	0·43

* For 200 g Ca in a skeletal mass taken as 1·9 kg for the child aged 5 years ; this contrasts with 1000 g Ca in a skeletal mass of 7 kg for the adult.

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